

# PV Integration and the 'Sunshine State' - Results, Tools, and Opportunities

Integrating PV in Distribution Grids:  
Solutions and Technologies Workshop

NREL, Golden, CO

October 22 & 23, 2015



Rick Meeker, P.E.  
[rmeeker@nhuenergy.com](mailto:rmeeker@nhuenergy.com)  
Nhu Energy, Inc.



# Sunshine State Solar Grid Initiative (SUNGRIN)

11/1/2013 – 2/28/2015. A DOE EERE Hi-pen Solar Deployment Project

*To gain significant insight into effects of high-penetration levels of solar PV systems in the power grid, through simulation-assisted research and development involving a technically varied and geographically dispersed set of real-world test cases within the Florida grid.*



Rick Meeker (PI), Mischa Steurer, Helen Li, Omar Faruque, Karl Schoder, James Langston, Harsha Ravindra, Mike Sloderbeck, Mike Andrus, Isaac Leonard, Ye Yang, Ali Hariri, Thierry Kayiranga, Matthew Bosworth, Dionne Soto, Krystal Wright



Dave Click, Bob Reedy



Energy Efficiency &  
Renewable Energy



# Four High-Pen PV Feeders

## Feeder 1

- 24 kV feeder, about 9 miles in length
- 12.6 MW solar PV
  - A single large plant about 4.8 miles from substation
- Over 200% penetration (of peak)
- Voltage regulation:
  - none
- Load:
  - Peak loading around 5 MVA. Typical daily peak < 2 MVA
  - Mix of residential and commercial, mostly residential, ~85:15%

## Feeder 2

- 12.47 kV feeder, 4.4 miles in length
- 2.6 MW Solar PV:
  - 2.25 MW installed near end of first long lateral (2x1 MW + several smaller)
  - 350 kW near the start of a 2<sup>nd</sup> shorter lateral
- 32% penetration (of peak)
- 1 recloser about 2.2 miles from substation
- Voltage regulation:
  - 4 capacitor banks
  - 1 step voltage regulator, near substation
- Load:
  - Peak loading around 8.1 MVA
  - Mix of mostly residential and commercial, ~40:60%

## Feeder 3

- 12.47 kV feeder, 4.5 miles in length
- 2.3 MW PV installed at the end of feeder.
- Voltage regulation:
  - 5 switched capacitor banks
  - 1 step voltage regulator.
- 26% penetration (of peak)
- Load:
  - Varies from 100A to 500A.
  - Mix of residential and commercial customers ~35:65% ratio respectively

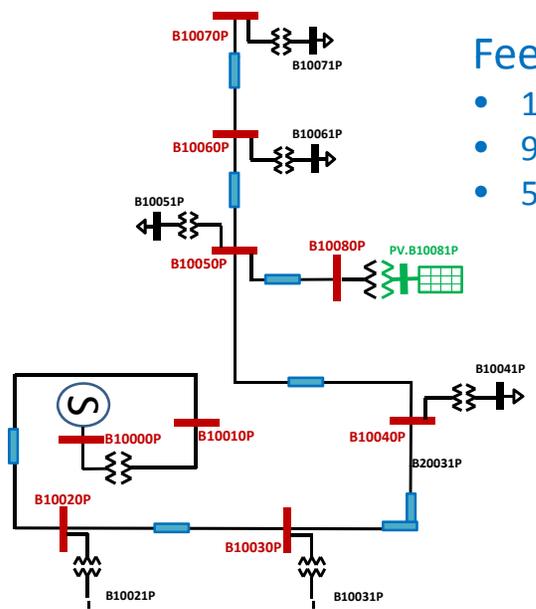
## Feeder 4

- 12.47 kV feeder, 6.7 miles in length
- 5.5 MW Solar PV, installed near midpoint of feeder
- Feeder minimum load around 0.5 MW and maximum load around 1 MW.
- Voltage regulation:
  - No voltage regulation devices.
  - Capacitor bank turned off after installation of PV.
- Over 500% penetration (of peak)
- Load:
  - 100% commercial / industrial

# Four High-Pen PV Reduced Feeder Models

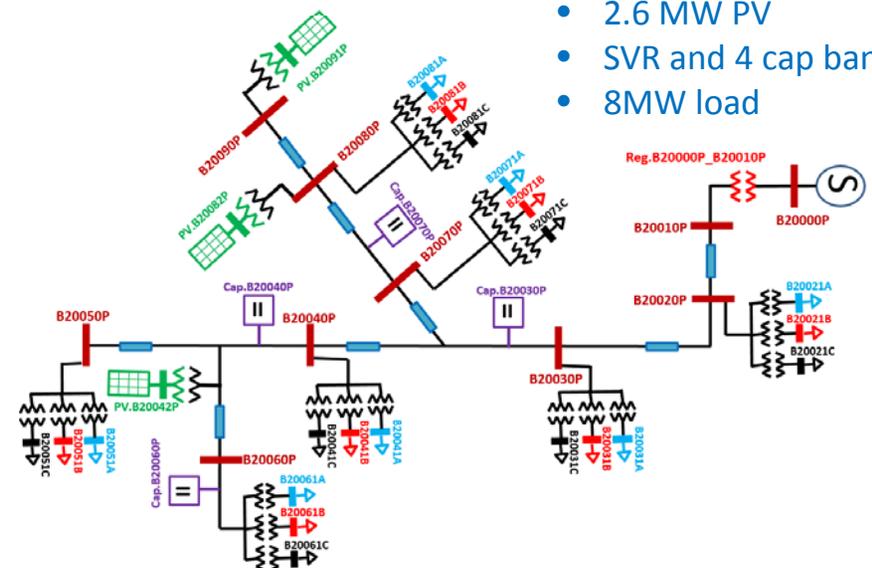
## Feeder 1

- 12.6 MW PV
- 9 miles long
- 5 MW load



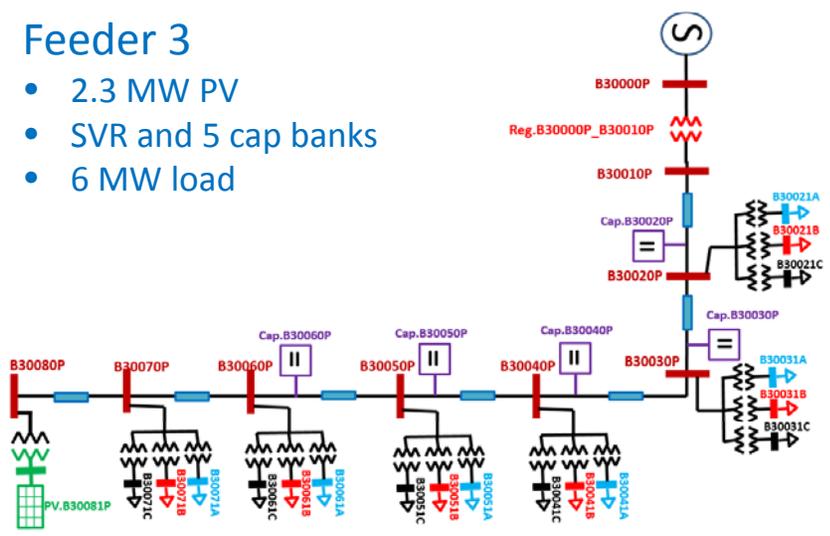
## Feeder 2

- 2.6 MW PV
- SVR and 4 cap banks
- 8MW load



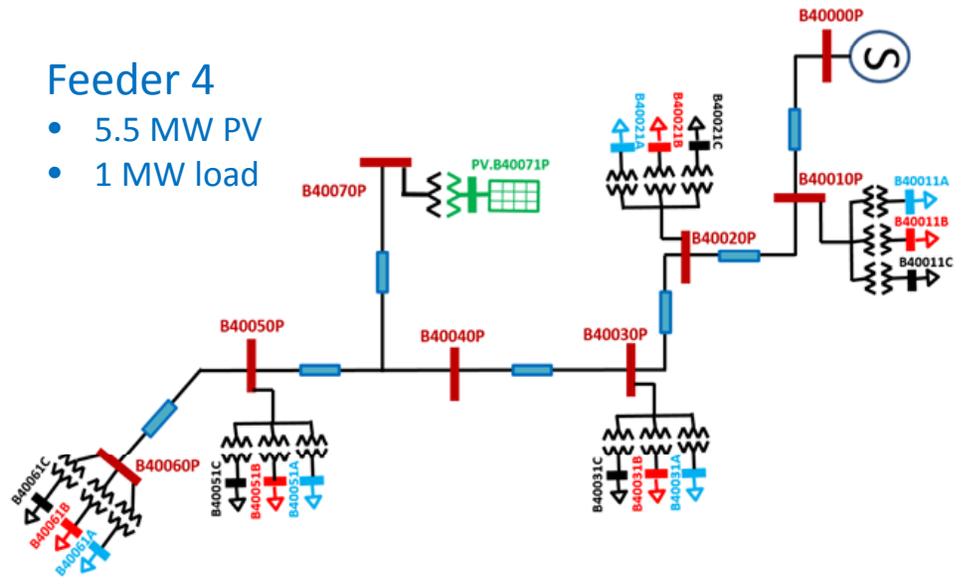
## Feeder 3

- 2.3 MW PV
- SVR and 5 cap banks
- 6 MW load



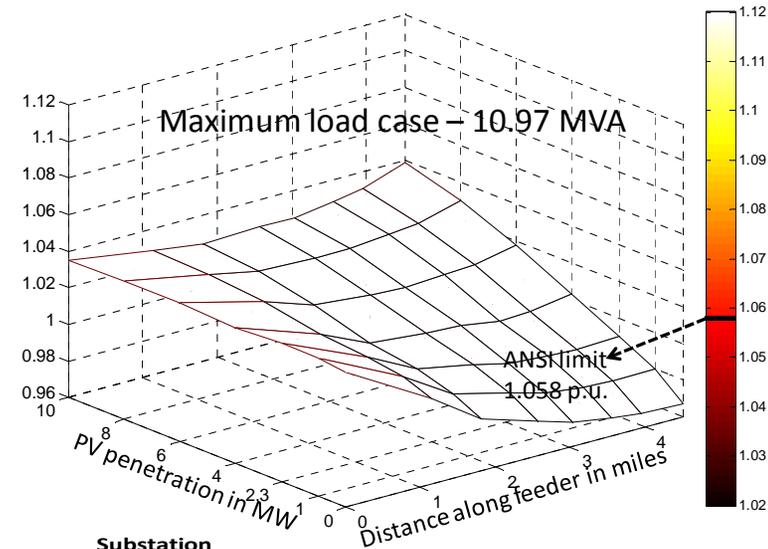
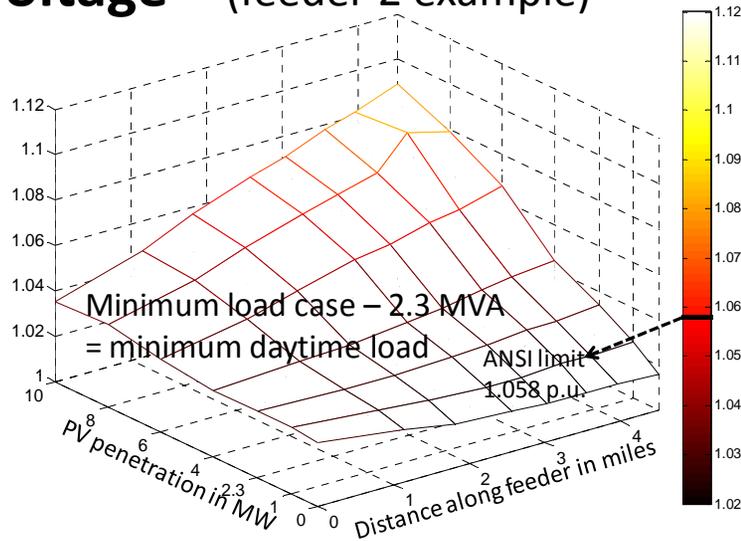
## Feeder 4

- 5.5 MW PV
- 1 MW load



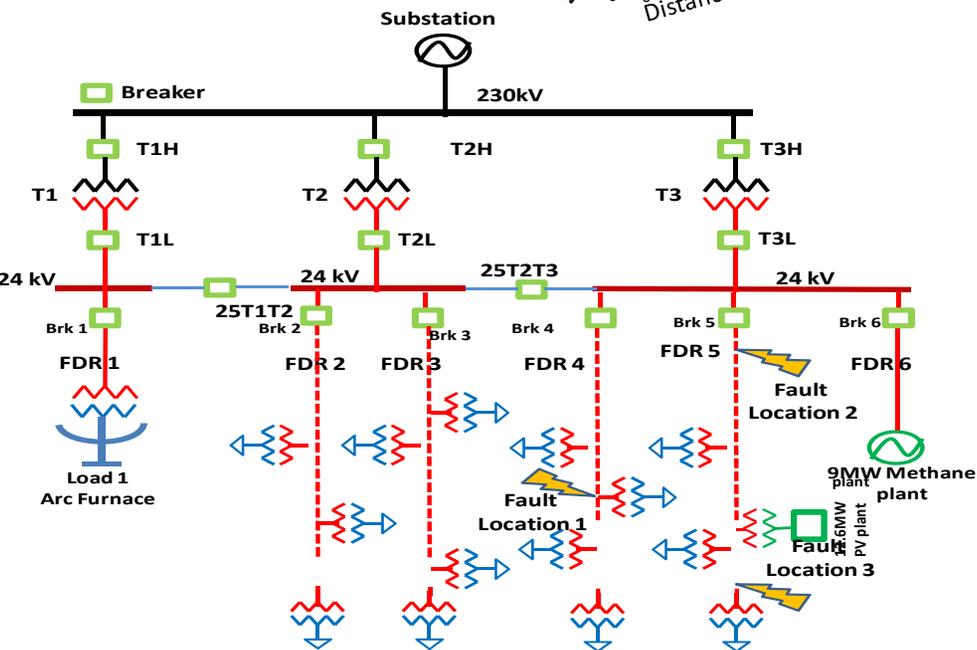
# Studies with RTDS models

- Voltage** (feeder 2 example)



- Protection**

- Reverse power flow trip of feeder breaker
- Fault current contribution by PV
- Sympathetic tripping of feeders
- Sensitivity to ground fault detection
- Effects of increased time to clear PV fault when compared to utility source alone

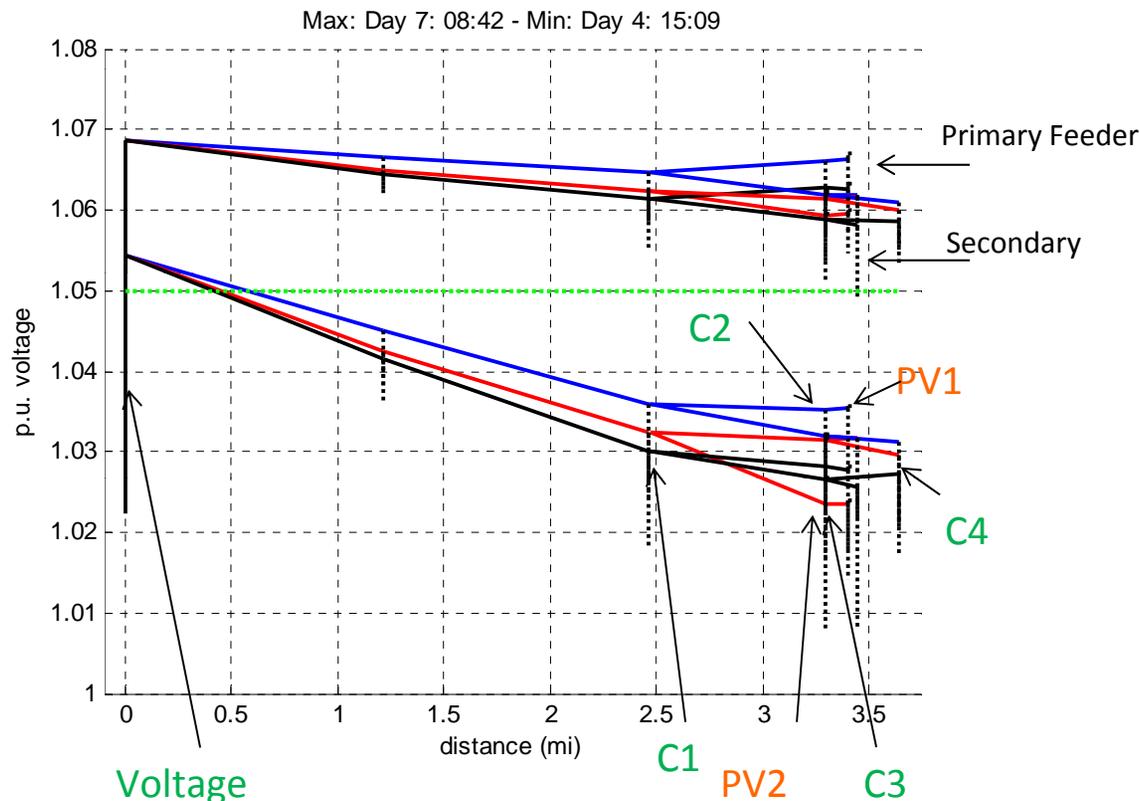


# Phase 4 Models, Data, and Tools

- Synthetic PV data sets
- Open-use OpenDSS models, data, and analytics
- Model reduction tool
- High-pen impact parametric study methods and tools

# Open Use Models

## Feeder 2 Example ...



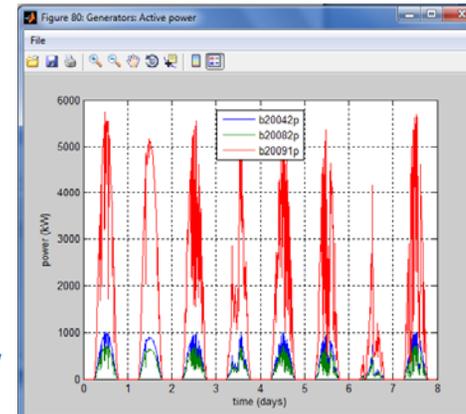
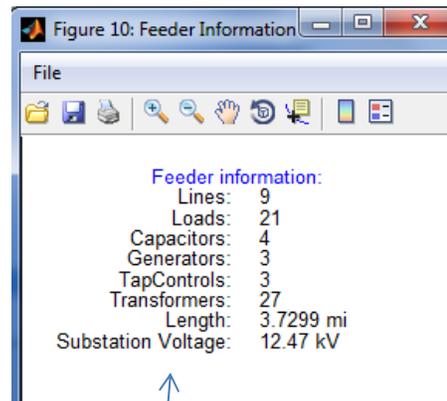
Voltage  
regulator

PV ... Solar PV plant

C ... Capacitor bank

- OpenDSS from MATLAB, using COM interface
- Includes MATLAB functions to generate and execute OpenDSS models and select data to be recorded
- Standard naming convention adopted throughout
- Released ready to run with three (3) fully functioning scenarios:
  - Base
  - Impact
  - Mitigation
- Includes GUI version
- Accompanied by documentation
- Available by download through web portal

# GUI-based Version



sg\_gui

### Distribution Feeder Analysis for DER Integration

Impact analysis through power flow time series studies

SUNGRIN, CAPS/FSU v0.5

Function Selection:

- Load data + Power flow/Time series
- Plot Min-Max Voltages
- Plot Feeder
- Plot Voltage Profile

Scaling: Load Gen. 1.00 1.00 pu

Case:

Load study | Info | Gen. Profile | Daily

Feeder: Feeder\_2\_MC.dss

Folder: C:\Users\rmeeker\CAPS\DOE\High\_Penetration\_Solar\_2009\Project\_Phase4\Models\sg\_ToolsModel\_Development\_04092015\Feed

Profile: Feeder\_2\_MC\_Profile.xlsx

Points: 11520, time step: 1 min, duration: 8.0 days

Msg: [1] Done.

Impact Analysis:

Voltage:

- Histogram
- Cumulative
- SubPlot
- Custom bins (pu): 0.90 0.95 0.98 1.00 1.02 1.05 1.10

Locate bus voltage excursions:

- Custom limits (pu): 0.95 1.05

Plot

Bus voltage levels:

- Custom limits (pu): 0.95 1.05
- Vpu vs. time
- Vpu vs. distance
- Data table
- Histogram (occurrence)
- Histogram (bins): 0.0 1.0 5.0 10.0 15.0 30.0 45.0 60.0
- Custom bins (minutes)

Switching:

Capacitors:  Histogram  SubPlot

Operations by element:  Plot  Daily

Cap.State Tap Pos.

Power:

Reactive contributions:  Show elements

Perform Function

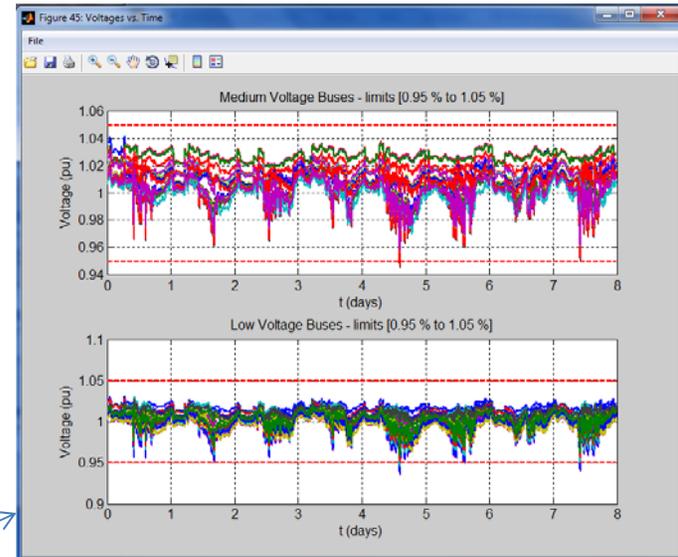
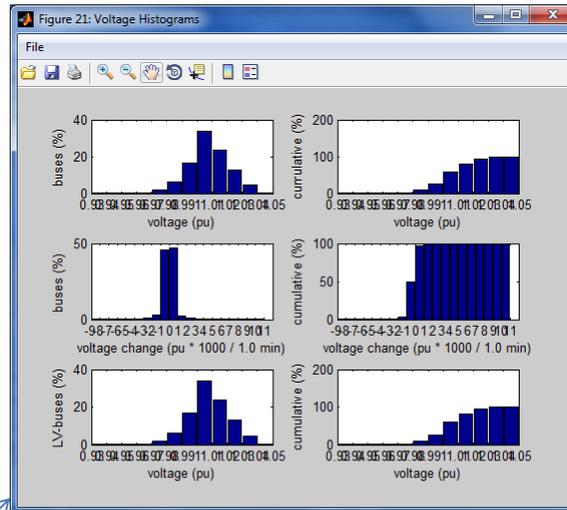
Min: Day 5: 14:21 - Max: Day 1: 11:18

p.u. voltage, Phase A-blue, B-red, C-black

distance (mi)

Developed with the support of U.S. Dept. of Energy under Awards DE-EE0002063 and DE-EE0004682.

# GUI-based Version



SUNGRIN, CAPS/FSU v0.5

Impact Analysis

Voltage

Histogram  Cumulative  SubPlot

Custom bins (pu): 0.90 0.95 0.98 1.00 1.02 1.05 1.10

Locate bus voltage excursions:  Custom limits (pu) 0.95 1.05

Plot

Bus voltage levels:  Custom limits (pu) 0.95 1.05

Vpu vs. time

Vpu vs. distance

Data table

Histogram (occurrence)

Histogram (bins)

Custom bins (minutes) 0.0 1.0 5.0 10.0 15.0 30.0 45.0 60.0

Switching

Capacitors  Histogram  SubPlot

Operations by element:  Plot  Daily

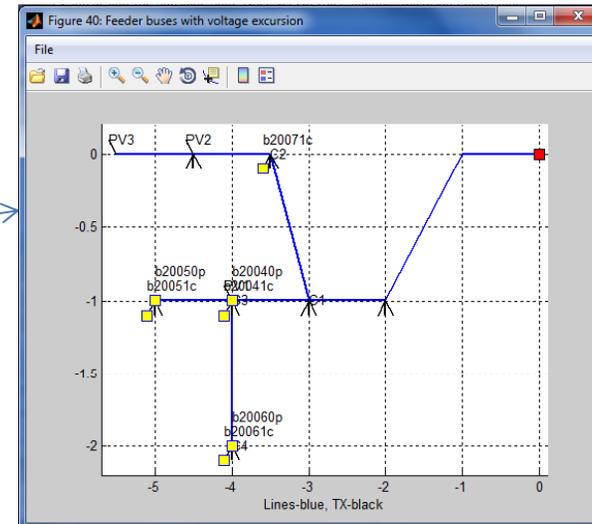
Cap.State Tap Pos.

Power

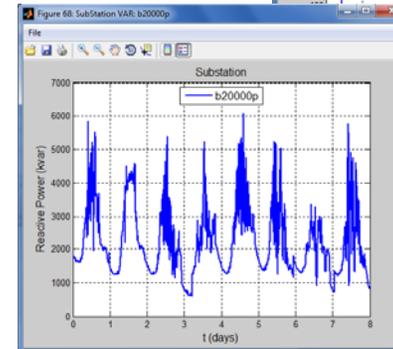
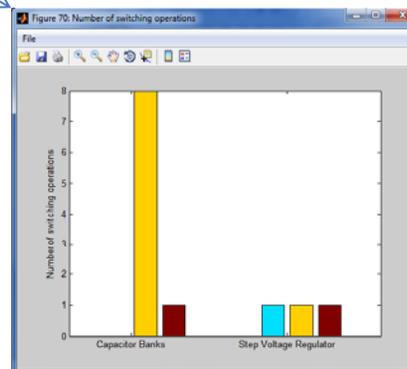
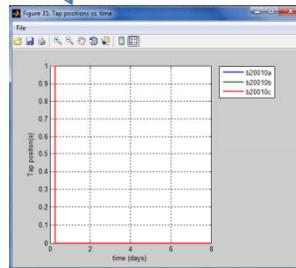
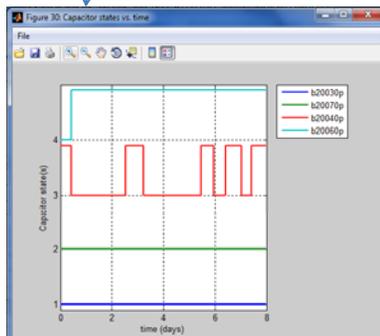
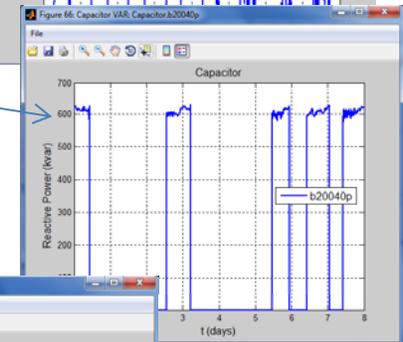
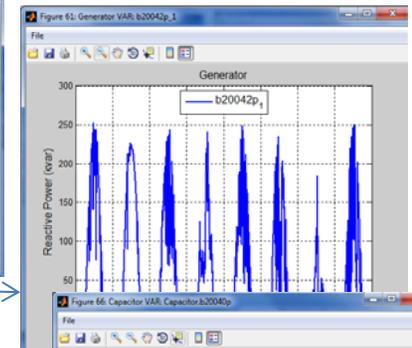
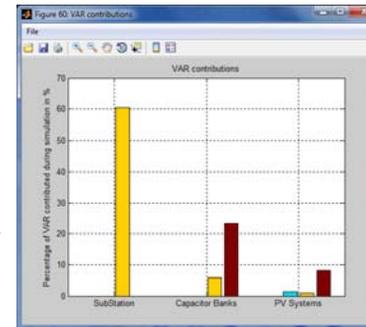
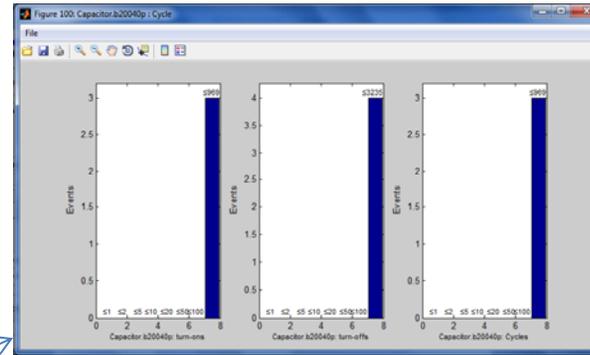
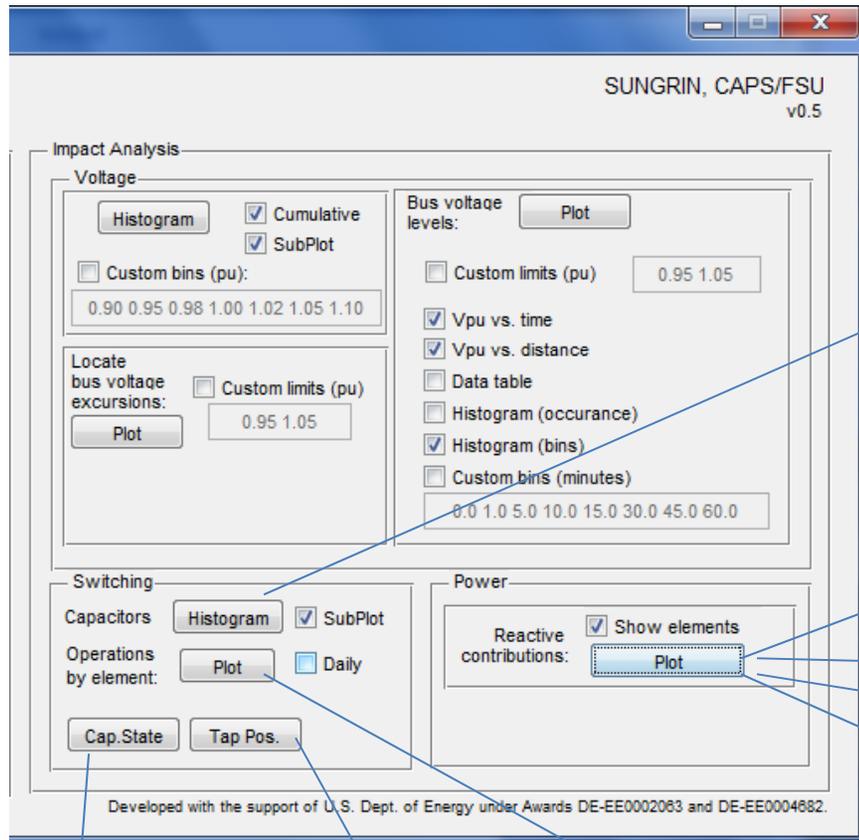
Reactive contributions:  Show elements

Plot

Developed with the support of U.S. Dept. of Energy under Awards DE-EE0002083 and DE-EE0004682.



# GUI-based Version



# Systematic Impact and Mitigation Assessment

Goal: Develop systematic methods and tools for understanding and assessing high-pen impact and mitigation measures

Experimental Design Tools & Approaches:

- Latin hypercube sampling (LHS)
- Factorial design
- ... other methods

PV and Load Profiles

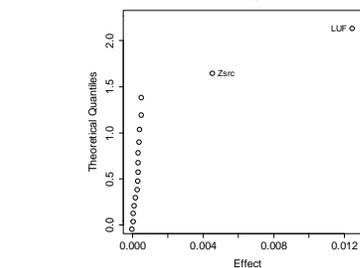
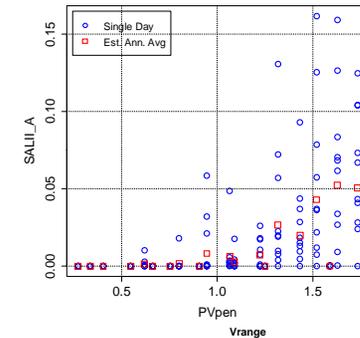
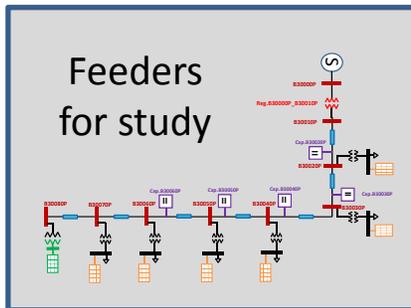


Simulation-assisted analysis system

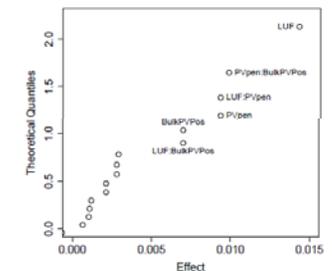
Parametric Studies / Factor Screening

OpenDSS Feeder Models

Feeders for study



No.	CapSwAvg	VregSwAvg
1	0.188	1.638
2	0.608	3.153
3	0.298	1.000
4	0.475	2.186
5	0.780	2.597
6	0.620	7.181
7	0.188	1.671
8	0.586	2.151
9	0.773	3.359
10	0.620	5.674
11	0.663	6.323
12	0.813	3.934
13	0.188	0.638
14	0.662	1.000
15	0.142	1.389
16	0.586	3.874
17	0.245	2.507
18	0.625	4.121
19	0.264	1.704
20	0.527	2.016



- Parameterization of system
- Response quantities
- Design of experiments
  - Multi-factor study method
  - Clustering to cover representative operating space

# New Metrics / Indices

Based on excursions outside of ANSI A or B limits (SALII\_A, SALII\_B, CALII\_A, CALII\_B)

- **SALII – System Average Load Impact Index**

$$SALII = \frac{\sum_{i \in L_{ex}} \int P_i(t) I_{ex}[V_i(t)] dt}{\sum_{i \in L} \int P_i(t) dt}$$

- **CALII – Customer Average Load Impact Index**

$$CALII = \frac{\sum_{i \in L_{ex}} \int P_i(t) I_{ex}[V_i(t)] dt}{\sum_{i \in L_{ex}} \int P_i(t) dt}$$

$$I_{ex}(V) = \begin{cases} 0, & \text{for } V_{limit-min} \leq V \leq V_{limit-max} \\ 1, & \text{otherwise} \end{cases}$$

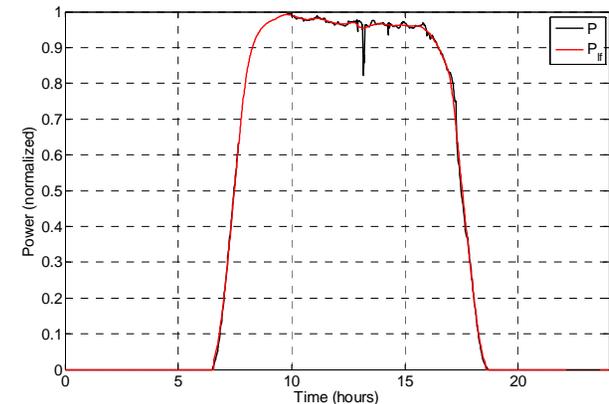
If the excursion of the voltage at a load were treated as an interruption, these indices reflect the proportion of the total energy to all customers and to affected customers that would be expected to be lost on a daily basis.

# High Frequency Variability Index

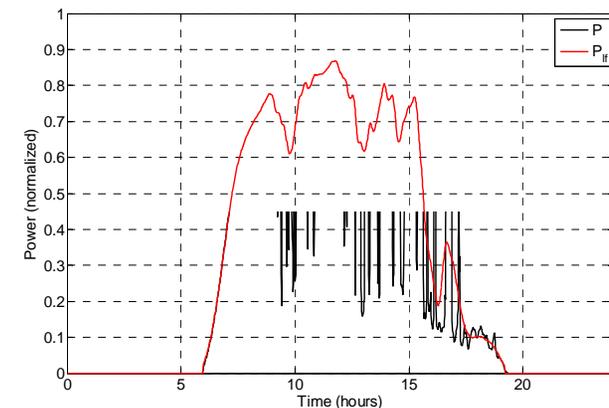
- Motivated by variability index [1] applied to characterization of irradiance data.
  - Computes the ratio of the “length” of measured irradiance profile the “length” of the global horizontal irradiance (GHI) curve
- Here a modified approach applied to PV power since:
  - Comparison to GHI may not be appropriate for tracking PV system.
  - Irradiance data is not provided in all data sets that were employed for constructing profiles
- Alternatively, compare “length” of power profile with that of filtered power profile
- For obtaining low frequency power profile, use second-order Butterworth filter with cutoff frequency of  $1.74e-4$  Hz (corresponding to 15<sup>th</sup> harmonic with a 1 day fundamental period)
- Scaling of normalized PV power
  - “Distance” measure of variability index uses incompatible dimensions, rendering it sensitive to units
  - Normalized PV power scaled by 1000 to obtain values comparable to irradiance values

$$HFVI = \frac{\sum_{k=2}^n \sqrt{[1000\hat{P}(k) - 1000\hat{P}(k-1)]^2 + \Delta t^2}}{\sum_{k=2}^n \sqrt{[1000\hat{P}_{lf}(k) - 1000\hat{P}_{lf}(k-1)]^2 + \Delta t^2}}$$

HFVI=1

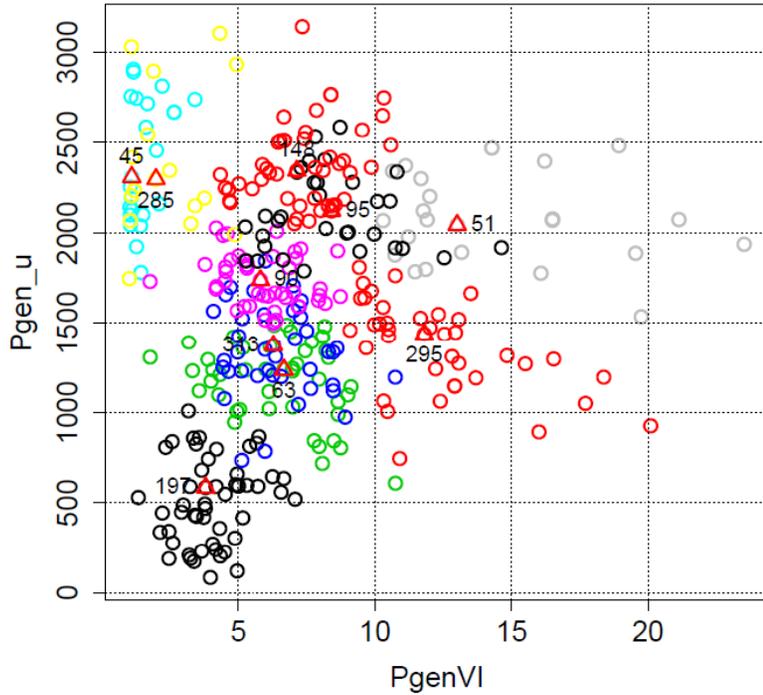


HFVI=10

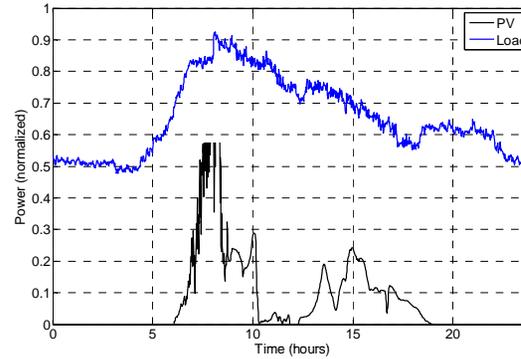


[1] Joshua Stein, Clifford Hansen, and Matthew J Reno. The variability index: A new and novel metric for quantifying irradiance and PV output variability. Technical report, Sandia National Laboratories (SNL-NM), Albuquerque, NM (United States), 2012.

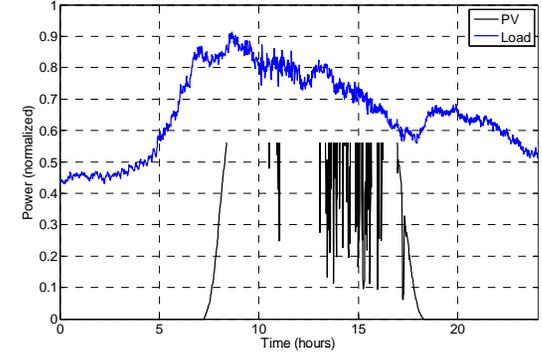
# Selection of Representative Subsets of PV and Load Profiles



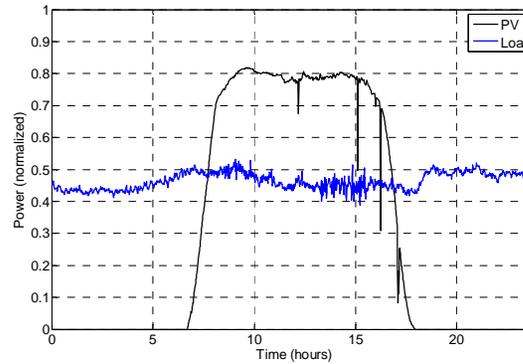
Clusters Selected using Pgen\_u, PgenVI, and Pload\_u  
Based on One Year Profile Set



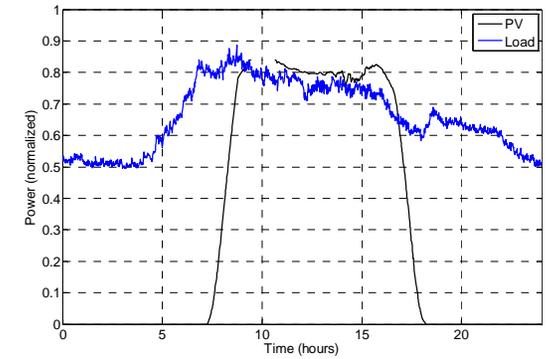
Profile Pair 197



Profile Pair 51



Profile Pair 285



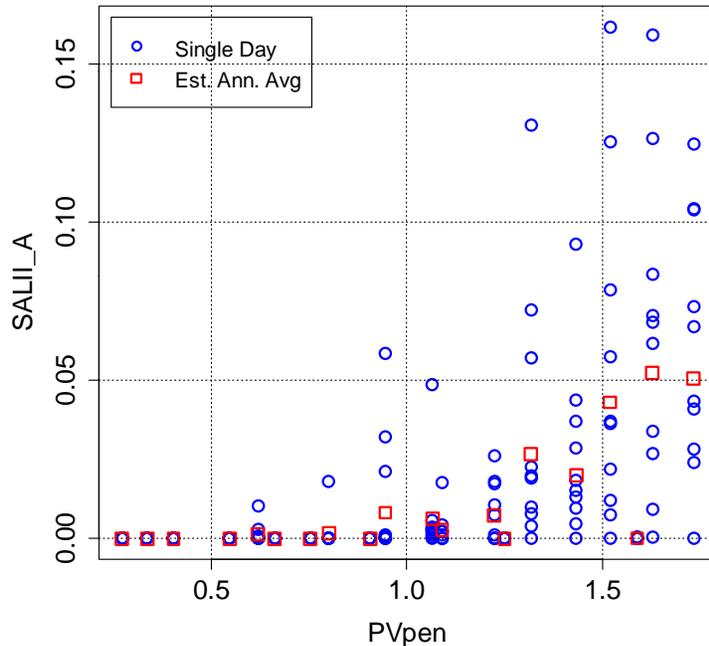
Profile Pair 45

Example Profile Pairs from the Selected Subset of Ten

# Systematic Impact and Mitigation Assessment

## - Example Results

Examine relationships between input parameters and output response quantities:



Attempt to fit quadratic regression models:

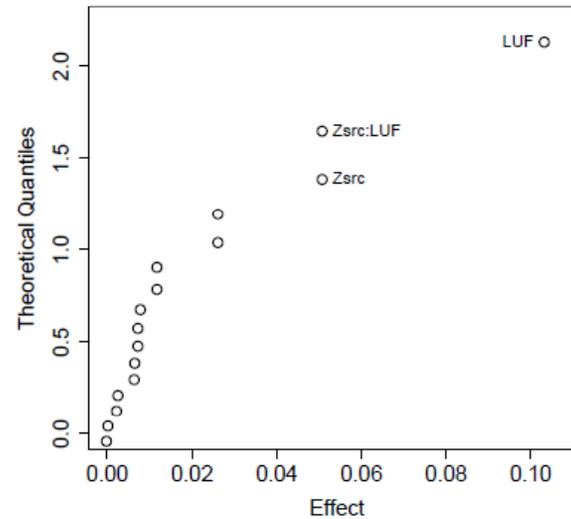
Response Quantity	Quant	Formula	$R^2$	$R^2_{adj}$	$\kappa$
CapSwAvg		$k_0 + k_1PVpen + k_2Zsrc + k_3LUF + k_4LUF^2 + k_5PVpen \cdot Zsrc$	0.791	0.716	3.09
VregSwAvg		$k_0 + k_1PVpen + k_2Zsrc + k_3LUF + k_4PVpen^2 + k_5Zsrc^2 + k_6LUF^2 + k_7PVpen \cdot LUF + k_8Zsrc \cdot LUF$	0.913	0.850	5.11
Vmax		$k_0 + k_1PVpen + k_2LUF + k_3LUF^2 + k_4PVpen \cdot LUF$	0.979	0.973	3.19
Vmin		$k_0 + k_1PVpen + k_2Zsrc + k_3LUF + k_4LUF^2 + k_5PVpen \cdot Zsrc$	0.986	0.981	3.09
dVmax		$k_0 + k_1PVpen + k_2LUF + k_3LUF^2 + k_4PVpen \cdot LUF$	0.979	0.973	3.19
Vrange		$k_0 + k_1PVpen + k_2Zsrc + k_3LUF + k_4PVpen \cdot Zsrc + k_5PVpen \cdot LUF$	0.969	0.958	2.86
SALII_A		$k_0 + k_1PVpen + k_2LUF + k_3PVpen^2 + k_4PVpen \cdot LUF$	0.922	0.901	3.36
CALII_A		$k_0 + k_1PVpen + k_2LUF + k_3PVpen^2 + k_4LUF^2 + k_5PVpen \cdot LUF$	0.922	0.895	4.43
SALII_B		$k_0 + k_1PVpen + k_2Zsrc + k_3LUF + k_4PVpen^2 + k_5PVpen \cdot Zsrc + k_6PVpen \cdot LUF + k_7Zsrc \cdot LUF$	0.948	0.917	4.26
CALII_B		$k_0 + k_1PVpen + k_2Zsrc + k_3LUF + k_4PVpen^2 + k_5PVpen \cdot Zsrc + k_6PVpen \cdot LUF + k_7Zsrc \cdot LUF$	0.952	0.923	4.26
FLLR_u		$k_0 + k_1PVpen + k_2Zsrc + k_3LUF + k_4PVpen^2 + k_5PVpen \cdot LUF + k_6Zsrc \cdot LUF$	0.997	0.996	4.06
RPFp		$k_0 + k_1PVpen + k_2PVpen^2$	0.969	0.966	3.17

# Systematic Impact and Mitigation Assessment

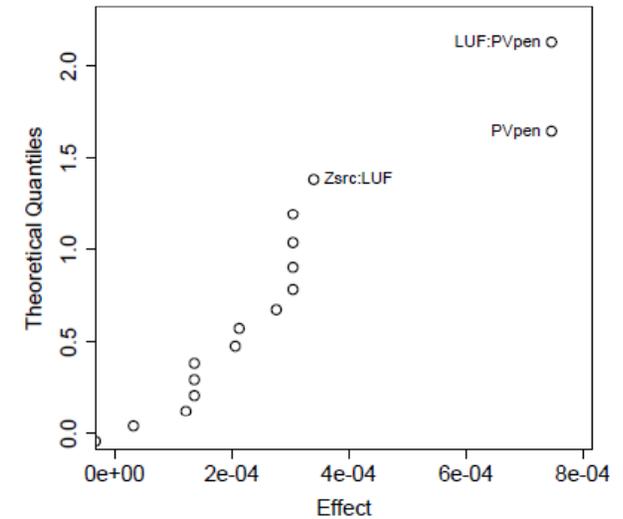
## - Example Results

Using a factorial design method:

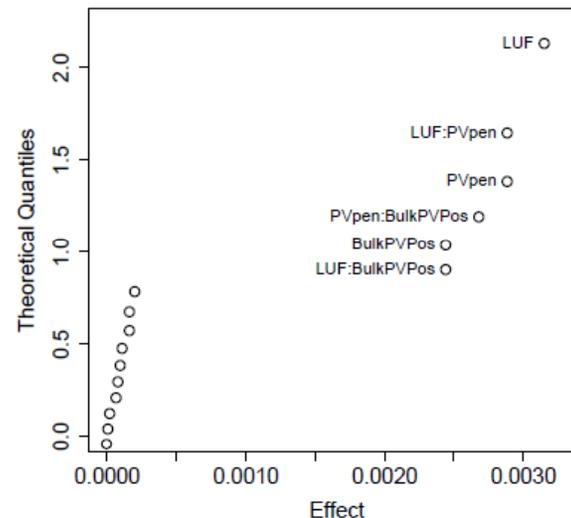
- Load impact index SALII\_A
- LUF influential in all four models
- Less impact on feeder 2
- Zsrc influential on feeder 1, but not PVpen
- PVpen and BulkPVpen play role in feeders 3 and 4
- Interaction of BulkPVpen particularly influential in feeder 4 (parts of feeder higher impedance)



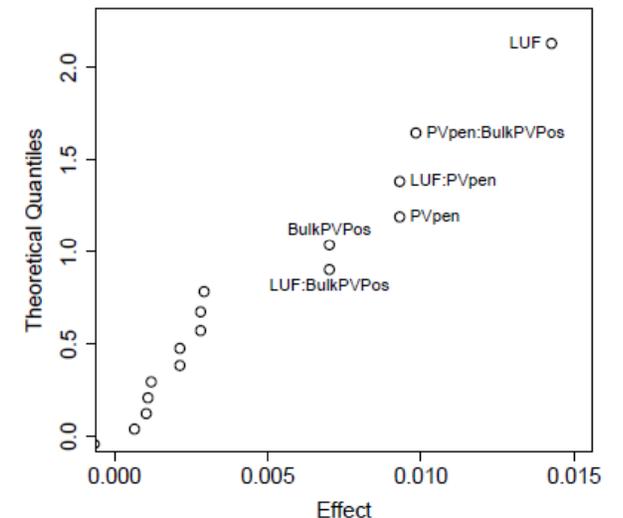
(a) Effects for SALILA (Feeder 1)



(b) Effects for SALILA (Feeder 2)



(c) Effects for SALILA (Feeder 3)



(d) Effects for SALILA (Feeder 4)

# Summary - Tools

- We've arrived at level of sophistication more commensurate with the challenges and opportunities
- Tools and methods for understanding and enabling high-penetration PV have progressed considerably in the last 3 years.
- Many may have obstacles to widespread use:
  - Variety of approaches and platforms
  - Custom scripting, coding, and interfaces
  - Learning curves steep in some cases,

# Summary – PV Integration

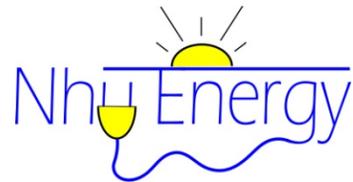
- Greatest effects surface as system-wide penetration reaches high levels
- DER, PV can make the grid more resilient if integrated into utility distr. operations
- Major benefit with lower integration complexity and cost is realizable by focusing first on larger grid-connected PV systems (100's of kW to 10's of MW on Distr. sys)
- Future:
  - We will end up at a state of substantially improved control on the system, and particularly all the way down to distribution and the customer.
  - We've yet to fully define and quantify the value of much improved control



---

THANK YOU!

Rick Meeker  
Nhu Energy, Inc.  
Tallahassee, FL  
[rmeeker@nhuenergy.com](mailto:rmeeker@nhuenergy.com)  
850-385-5100



[www.nhuenergy.com](http://www.nhuenergy.com)